BBC

Research Department Report

Beamforming devices and feed structures for a DBS flat-plate antenna

S. Wakeling, B.Sc., C.Eng., M.I.E.E.

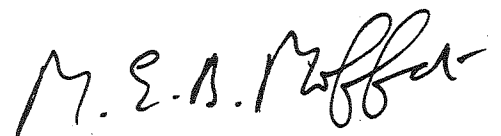# BEAMFORMING DEVICES AND FEED STRUCTURES FOR A DBS FLAT-PLATE ANTENNA

S. Wakeling, B.Sc., C.Eng., M.I.E.E.

Summary

A flat-plate antenna is considered to be a viable alternative to a parabolic dish for the reception of Direct Broadcast by Satellite (DBS) television signals. A flat-plate antenna should form beams over a range of different directions, pointing at the satellite from different orientations on the ground. A beamforming device can produce several beams from a given array. A feed network is needed to collect all the signals from the array elements and input them to the beamforming network.

The types of feed structure which could be used with the flat-plate antenna have been considered and the design of a corporate feed structure is reported. A number of steering mechanisms and beamforming devices have also been examined. A microwave lens proved to be the only option which could form beams from such a large array and be constructed using low cost materials. The design, construction and testing of an experimental Rotman lens is reported here.

Issued under the Authority of

**Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION**

Head of Research Department

BEAMFORMING DEVICES AND FEED STRUCTURES FOR A DBS FLAT-PLATE ANTENNA

S.Wakeling, B.Sc., C.Eng., M.I.E.E.

BEAMFORMING DEVICES AND FEED STRUCTURES FOR A DBS FLAT-PLATE ANTENNA

S. Wakeling, B.Sc., C.Eng., M.I.E.E.

1. INTRODUCTION

A flat-plate antenna may be a suitable alternative to a parabolic dish for the reception of Direct Broadcast by Satellite (DBS) television signals. A companion Report[1] outlines a design which may be viable. The advantages of a flat-plate antenna with beam steering are fairly obvious; it is less obtrusive than a dish, the wind loading is less and the mounting arrangement simpler. Also, unlike a conventional parabolic dish, rain and snow, which can attenuate the signal, cannot collect in it. The antenna must have a similar overall gain to a parabolic dish so the losses in its feed system must be kept to a minimum. It must also be able to compete financially with a parabolic dish so it is essential that its component parts can be made using low-cost materials and production techniques.

The proposed antenna consists of an array of linear elements with a polariser in front to convert to circular polarisation. The design and performance of the elements and polariser are dealt with in two other Reports[2,3]. The basic idea behind a flat-plate antenna is that it can be mounted flat on the most conveniently facing wall of a house and steered electrically to point at the satellite. This Report describes the method used to steer the array and the feed structure used to gather the energy from the individual elements.

The antenna is expected to receive signals from a specified angular sector depending on the position of the geostationary DBS satellite and the orientation of the wall on which it is mounted. A polar method of beam steering has been proposed[1] which requires the array to be steered in one plane only, with the antenna being rotated on the wall to produce the elevation necessary. The signal received by each individual element is collected in one plane of the array and connected to a beamforming network to allow the beam to be steered in the other plane.

This Report investigates several types of steering mechanisms, including switchable delay lines and varactor phase shifters, and beamforming networks such as Butler matrices and the microwave lens. The design and performance of a microwave lens is reported. Also, two possible feed strategies are considered; a series feed and a corporate feed network. The advantages of each type of feed are considered and the design and performance of a corporate feed network outlined.

2. FEED NETWORKS

The function of the feed structure is to gather the energy from each antenna element and to provide a single output*. To do this efficiently it must have a low loss since it has been shown that the feed structure can fundamentally limit the gain of the whole antenna[4]. To ensure low loss, the feed line should be an enclosed structure, and thus not itself be a source of radiation. The use of low loss materials is also important and the feed structure should be compatible with the operation of the beam-steering mechanism.

Feed structures can either be located behind the array or formed on the same substrate. However, as there is very little space available between the elements of the proposed flat-plate antenna, any integral feed system would need to be very compact.

There are, in general, two classes of feed network which will be considered: series feed and corporate feed.

2.1 Series feed networks

A series feed is a compact feed system for linear arrays. The radiating elements are attached periodically to a transmission line thereby forming a travelling-wave array. It can be represented as a loaded transmission line as shown in Fig. 1.
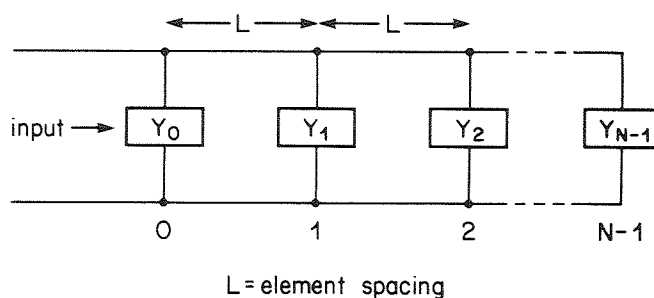
Fig. 1 - Series feed network.

The phase of the radiating elements (and hence the radiation pattern) is determined by their spacing along the transmission line. As the frequency is changed a progressive phase shift is introduced along the array. This causes the main beam direction to change with frequency and is an important and limiting characteristic of a travelling-wave array. For

---

* Although the proposed flat-plate antenna is a receiving device its operation is easier to describe in the transmitting mode, and since reciprocity applies, this approach is used below.

DBS reception, a geostationary satellite will be in a fixed position with respect to the receiving antenna, so this mispointing of the main beam gives an apparent loss in gain. This is known as scanning loss. This problem will be compounded for the proposed flat-plate antenna design which is required to produce several beams at different slew angles.

The loading on the transmission line depends on the array element used and the spacing of the elements has to be chosen to produce the required phase distribution across the aperture. A series feed system is complicated to design because the impedance looking into the array changes along its length. This is caused by different numbers of elements loading the transmission line and leads to a large range of impedances required to match to the array elements. Therefore, a large number of matching sections would be required and the bandwidth of the feed structure would be reduced. Also, to provide the corresponding amplitude distribution across the elements requires an N-variable optimisation procedure which is very involved if losses in the line, or the susceptance loadings of the elements, are significant. However, for long arrays it is usually sufficiently accurate to perform a reverse iteration procedure starting at the end of the array[5].

Any feed structure will also have some loss in the feed lines, but this can be reduced for a series feed by feeding the array at the centre and using two half-length transmission lines. A problem with this type of feed is that each half of the array has waves travelling in opposite directions, and hence the beam from each will have a different squint angle, severely limiting the bandwidth available from this arrangement.

2.2 Corporate feed networks

A corporate or parallel feed structure has equal lengths of line from the input to each element and so solves the problem of the scanning loss which is a particular disadvantage of a series feed. The corporate feed system splits the power between N elements with a prescribed amplitude distribution while maintaining equal path lengths. Fig. 2 shows an example of a corporate feed suitable for a linear array which provides a linear amplitude distribution.
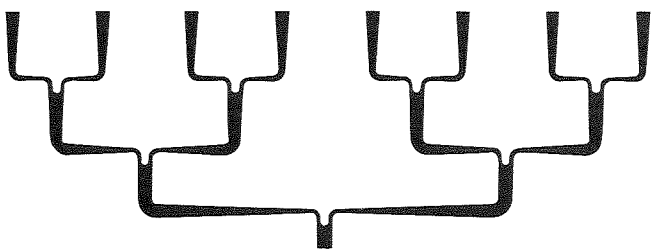

Fig. 2 - Corporate feed structure.

Corporate feed structures have higher line losses than series feed networks because of the longer lengths of line used, but they do not suffer from scanning loss (see Section 2.1). Series feeds have the advantage that they are compact, but the range of impedances required to match to the whole sub-array is large, thus reducing the bandwidth of the feed.

3. STEERING MECHANISMS AND BEAMFORMING NETWORKS

The requirement specified in Ref. 1 is for a steering mechanism to produce beams to cover an angular sector 16° to 52° to one side of broadside. The position of the main beam of an antenna can be chosen by adjusting the phase of the signals before combining them so that the radiation from a particular direction adds up in phase. This technique is known as the phased array principle and has been used in military applications to steer radar beams. Some of the methods of implementing this technique are examined below.

The requirement for a steering mechanism with a continuously variable main beam can be modified to a requirement for a set of fixed beams plus a small mechanical adjustment on the mounting. Beamforming networks produce a set of beams from a given array. The beam in the most suitable direction would be connected to the receiver. This allows just one flat-plate antenna to be used for all orientations without the need for a complicated set-up routine by the installer.

If the flat-plate antenna were to be a device which could receive signals from more than one satellite, a beamforming network could be designed to achieve this. It would be possible to align each beam with a different satellite at the expense of the antenna mounting flat on the wall. However, the current study is of an antenna which can point at one satellite only from the optimum wall of a house anywhere in the UK[1].

An important concept to be aware of when designing beamforming networks is that of orthogonal beams[6]. It has been shown from energy conservation principles that a beamforming network can only be theoretically lossless if the beams it produces are orthogonal. In practice, orthogonal beams will result in the minimum loss condition. Methods of beam steering which produce one beam only are not subject to the restriction of orthogonal beams; however, devices which are essentially multiple beamforming networks have to be designed according to this principle or else suffer high losses.

It is important to remember that multiple beams from a flat-plate antenna cannot be simply slewed around in angular space. As the slew angle is increased, the beams become wider and their gain reduces. To maintain orthogonality the relative angular spacing of the beams will increase. For those familiar with this principle, we are said to be slewing in 'sin θ' space.

3.1 Switchable delay lines and phase shifters

A slewed beam can be obtained from an antenna by imposing a phase taper on the feeds to its elements. There are several methods of achieving the required phase taper across an array; either using variable lengths of transmission line to introduce delay or by using phase-shifting components. PIN diodes can be used to switch lengths of transmission line to alter the delay, and varactor diodes can be used to alter the impedance of a line, resulting in a phase shift. Two other methods described are the cross-fade method and the local oscillator and mixer technique.

Varying lengths of transmission line can be arranged in various combinations to allow a beam to be produced in any direction under the control of PIN diode switches. However, for arrays with a large number of elements, a very large number of PIN diode switches are required.

Radio frequency phase-shifters are devices which can produce a variable phase shift in a signal. They often consist of a length of transmission line and a varactor diode which can be set to alter the apparent impedance of the transmission line. They would have to be adjusted on installation to give the required beam slew for a particular configuration.

The cross-fade method of phase-shifting takes the input signal and divides it into three equal components which it then delays so that they are each 120° apart. By attenuating the signals before re-combining them a signal of any phase can be produced. One way of attenuating the signals is by using PIN diode switches as a variable resistor and using an analogue DC voltage to control it. Unfortunately, the attenuation of the component signals introduces a large loss into the network so that this method can only be considered if the signal is amplified first.

A novel method for producing a continuously variable phase shift across an array of elements uses a distributed front-end amplifier and mixers. A local oscillator feeds a mixer for each element or group of elements to be steered and the phase shifts are obtained from the delays in the feed line to the mixers.

By altering the frequency of the local oscillator the phase shifts produced in the fixed lengths of line will alter. However, this method suffers from having a variable intermediate frequency and depends on the availability of cheap head amplifiers and mixers at 12 GHz. This method also depends on the stability of the local oscillator.

Most of these methods require the use of large numbers of expensive RF components: PIN diode switches or RF mixers and amplifiers. Therefore, although they may be suited to high-specification military applications, they become prohibitively expensive for a viable commercial flat-plate antenna design. New technology may mean that this situation may change in the future and they can then be reconsidered.

3.2 Blass and Butler matrices

A Blass matrix is a beamforming feed for a linear array which forms multiple beams by means of constant phase ramps. It is based on a series feed system where the multiple beams are generated by coupling several feed lines into branch lines by means of directional couplers, see Fig. 3[7]. Each feed line generates one beam in space and the phase shift between radiating elements is determined by the tilt introduced by the feed lines. The Blass matrix can be designed using true time delay to form the multiple beams so the beam directions remain stationary with frequency.

Fig. 3 - Series-fed multiple beamforming network – Blass matrix.
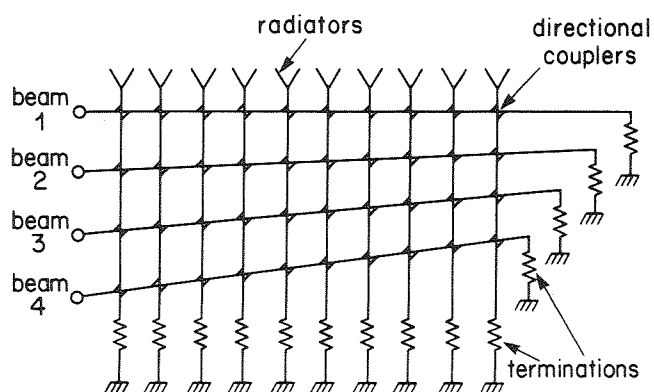
The Butler matrix is based on a parallel feed network and uses directional couplers which have a 90° phase-shifting property and fixed phase-shifters to produce the required phase tapers for each beam, see Fig. 4.

A signal input at any beam port excites all the array elements with equal amplitude but with phase differentials which are odd multiples of 180°/N. The

N array elements

fixed
phase-
shifter

hybrid

-45° -45° -45° -45°

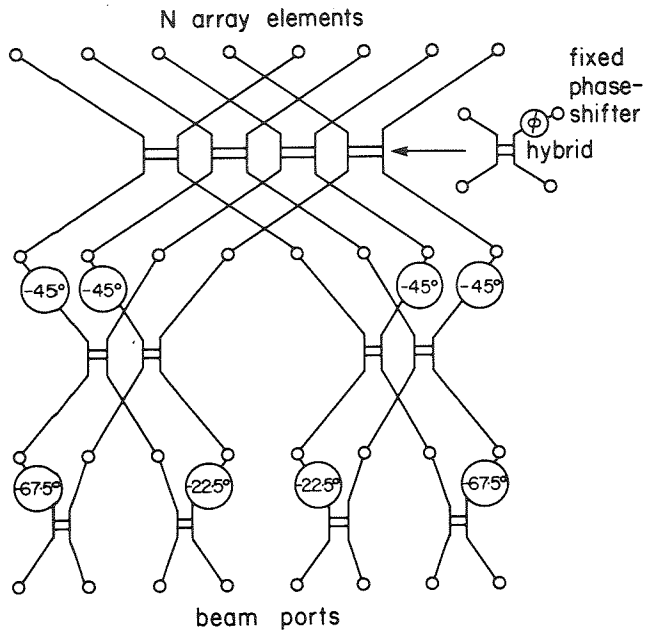-67.5° -22.5° -22.5° -67.5°

beam ports

Fig. 4 - Multiple beam Butler matrix feed.

matrix is designed to give an orthogonal beam set at the design frequency and consequently its beams scan in angle as the operating frequency changes. The losses within the network also increase as the beams become non-orthogonal. These are undesirable features for the reception of DBS signals because the satellite remains in a fixed position with respect to the antenna.

The construction of the Butler matrix is more difficult than the Blass matrix because a large number of transmission line crossovers are necessary, requiring the use of multi-layered circuitry. Also, with both the Butler and Blass beamforming networks, the hardware complexity grows with increasing array size and they are both judged to be unacceptably complex for arrays of more than 16 elements. For N elements and B beams, the Blass matrix requires $N \times B$ directional couplers. The Butler matrix requires $N/2 \log_2 N$ couplers regardless of the number of beams required, unless it is greater than N, but also uses phase-shifting components. For the proposed flat-plate antenna the number of sub-arrays to be steered will be 50, resulting in very large numbers of couplers being required. Since directional couplers are not easy to manufacture using low cost techniques, this type of beamsteering was not considered in detail for the flat-plate antenna.

3.3 Microwave lenses

A microwave lens is a multiple beamforming device which can produce a number of beams over a specified angular range. A phase taper is produced by using the time delay introduced by differing path lengths of transmission line connected to the array elements. Because the lens is essentially a time delay

device, its beams remain stationary in space as the frequency varies, although they will only be truly orthogonal at the design frequency in the centre of the band.

A microwave lens is a symmetrical device producing a set of orthogonal beams centred around broadside. The requirement for the DBS flat-plate antenna is. for beams which cover an angular sector 16° to 52° to one side of broadside. The beams produced by the lens can then be modified to cover the required angular sector. This is achieved by changing the length of the set of lines connecting the lens to the array. The beams remain orthogonal but their spacing increases as their scan angle becomes further from broadside.

A microwave lens is so named because the path lengths through it are calculated by geometrical optics principles, that is, assuming the RF signal transmitted through it can be drawn as rays. How valid this assumption is depends on the design and construction of the lens and a set of stringent design rules exists[6].

There are two types of microwave lenses; those which employ dielectric materials to focus the energy (which are analogous to optical lenses) and constrained lenses which rely only on differing path lengths to focus the energy. The lens designs considered for use in the flat-plate antenna are of the constrained type where the energy propagates in one plane only, constrained by two ground planes. Fig. 5 shows a small microwave lens connected to a planar array. The beam ports transmit or receive the signals for each beam direction and the array ports connect to the array elements. The ports themselves are flared to act as impedance transitions between the 50Ω connecting lines. and the low impedance of the lens cavity. The

beam
ports

lens
cavity

coaxial
lines

antenna
array

wavefront

signal

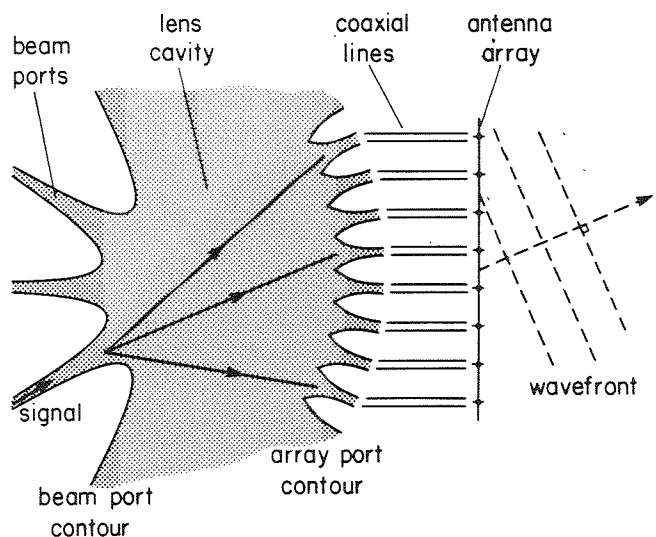array port
contour

beam port
contour

Fig. 5 - Lens-fed array system.

focusing of the energy from all the array elements occurs in the lens cavity, with the focal points of the lens lying on the beam port contour.

The optimum type of microwave lens depends on the geometry of the array aperture. The proposed flat-plate antenna is a linear array which will require a linear phase taper across it to produce slewed beams. Two lens designs are particularly suitable for use with a linear array, the Ruze lens and the Rotman lens. The primary difference between these two designs is that the Ruze lens has fixed line lengths connecting to the array while the Rotman design allows these lengths to vary. This extra degree of freedom allows a Rotman lens to be designed which has a better phase performance than the Ruze lens. The detailed design of a Rotman lens suitable for use with the flat-plate antenna is given in Section 6.

4. MATERIALS AND CONSTRUCTION TECHNIQUES

It is of prime importance that the materials and production methods used in the construction of a flat-plate antenna are inexpensive and suitable for mass-production processes. For these reasons, the components of the flat-plate antenna system were etched on copper electro-deposited on a polyimide film and a low-loss foam was used as the substrate. Aluminium plates or pieces of unetched copper-clad polyimide film were used for the triplate ground planes.

The attenuation of the triplate transmission system is determined by the copper loss, the dielectric loss of the materials used and the design of the transmission lines. The dielectric loss is given by the loss tangent of the transmission medium, which for triplate is any material between the ground planes and the centre copper conductor. In theory, this would be only the low-loss foam but in practice the losses caused by the polyimide film and the adhesive used to stick the foam to the film are the most significant. However, this loss can be reduced by using copper deposited on both sides of the central layer of polyimide film, resulting in no field in the film in a triplate transmission system. The copper loss is related to the area of copper making up the central conductor and is less for wide, low impedance transmission lines.

A problem arises if there are imperfections in the construction which result in discontinuities in the triplate transmission line. These cause parallel plate modes to be launched which propagate between the ground planes and interfere with the symmetrical triplate transmission mode. These unwanted modes are kept to a minimum by ensuring that the construction is symmetrical from the central conductor to each

ground plane, and by replacing foam with microwave absorber in areas which are not required to propagate a triplate mode. Fig. 6 is a photograph of an experimental lens showing the position of the wedges of absorber in relation to the triplate transmission lines of an experimental lens. Strips of absorber were also used to prevent the reflection of any energy incident on the side walls of the lens. To complete the construction, the transmission area between the absorber is filled with microwave foam and a top ground plane is added.
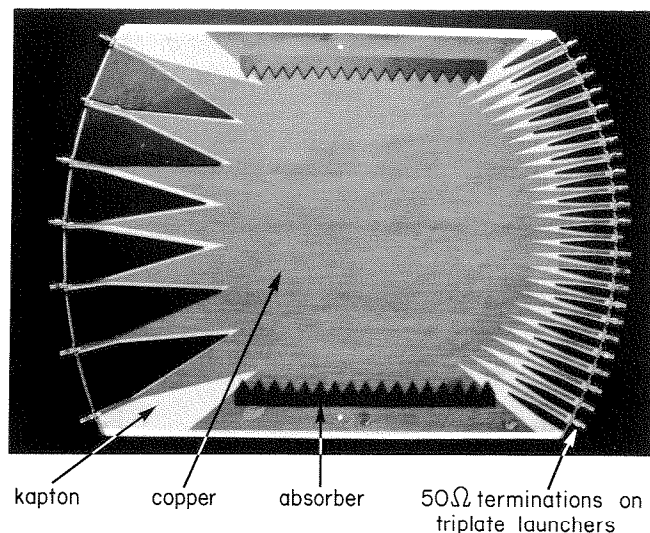

kapton   copper   absorber   50Ω terminations on
triplate launchers

Fig. 6 - Relative position of absorber within the microwave lens.

In general, the constructional tolerances relating to the etching processes are better than 0.1 mm. The limitation in the construction is the mounting of the triplate-to-SMA connectors. These can only be positioned to within about 0.5 mm and any such errors in the electrical path length to the array will affect its performance. These triplate launchers also have a significant voltage reflection coefficient and so contribute a significant amount to the overall loss of the feed and beamforming network. The reflections cause additional problems if they can propagate within the triplate structure and interfere with the wanted signal. However, in a final production antenna it should be possible to eliminate most of the connectors and interconnect the components of the flat-plate antenna using triplate transmission lines. This would reduce the loss in the system and the level of the internal reflections would be significantly lower.

5. DISCUSSION

So far in this Report, several alternatives have been discussed for the feed structure and steering mechanism for the proposed flat-plate antenna. Obviously a suitable feed structure and beamforming network needed to be chosen for the demonstration

antenna. The context in which these decisions were made is important. The specification is for an antenna to cover a defined angular range with a certain gain. This meant that the feed structure had to produce a number of beams with low-loss. However, it was also critical that the materials and production methods were low-cost and research time should be kept to a minimum.

On balance a corporate feed structure was chosen for a number of reasons. They are more straightforward to design than series feeds and do not suffer from scanning loss which may have interfered with the operation of the beamforming network. The corporate feed was mounted behind the array elements to ease the problem of space availability and designed and constructed to minimise its loss. The detailed design is given in Section 6.

However, it is possible that future development work would allow a series feed structure to be investigated more fully, in particular to see if the problem of scanning loss can be solved. Changing to a series feed would further reduce the losses in the feed structure.

Conventional beam steering methods using phase-shifting components or switched delay lines proved to be far too expensive because of the large number of discrete RF components required. This situation may of course change in the future, but for the time being these methods had to be rejected. Similarly, beam forming matrices use large numbers of directional couplers and are exceedingly complex for large arrays.

A microwave lens satisfies all the requirements of the proposed flat-plate antenna and can be made using low-cost materials and techniques. The design and performance of a Rotman lens is given in Section 7 and, so far, it has shown no obvious disadvantages.

6. DESIGN AND CONSTRUCTION OF A CORPORATE FEED

A corporate feed network has been designed to provide uniform illumination to the sub-arrays from each array port of the lens. The loss it introduces is of primary importance as the performance of a flat-plate antenna is fundamentally limited by its aperture and the losses in its feed structure. The corporate feed structure has potentially high losses due to the long lengths of transmission line involved. The feed has to be designed and constructed in a way that will minimise this loss. The phase velocity of the signal in the line is also important as any phase variations in the contributions of the various array elements will upset the performance of the beamforming network.

A corporate feed network was designed using quarter-wave transformers at the line splits and the corners were cut to optimise matching as recommended in Ref. 8. A section of the feed structure is shown in Fig. 7.

The feed is based on an impedance of 50 Ω and therefore quarter-wave matching sections of 70 Ω are required at each line split.

The measured loss of the feed structure was around 3-4 dB/m but this could be reduced to 1-1.5 dB/m if the adhesive and polyimide film were omitted. The measured loss of the corporate feeds varied slightly for each sub-array, mainly because of varying reflection coefficients at the connectors, but it was around 2 dB. It may be possible to reduce this in a production prototype of the flat-plate antenna where the adhesive, film and connectors could be omitted. Alternatively, the problems associated with a series feed structure could be solved.

7. THE MICROWAVE LENS

As described previously, a microwave lens is a beamforming device where a signal fed into one of several input or beam ports produces a phase taper across a set of output or array ports to excite the array to produce a beam in a given direction. The lens focuses the energy from the array onto the circular beam port contour. A Ruze lens has two perfect focal points on the beam port contour whereas a Rotman lens has three. The focusing is a consequence of providing equal electrical path lengths from a given
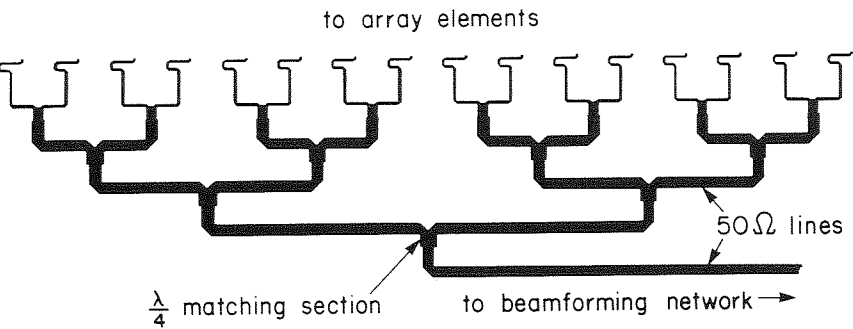
to array elements

Fig. 7
Section of a corporate feed.

$\frac{\lambda}{4}$ matching section   to beamforming network →
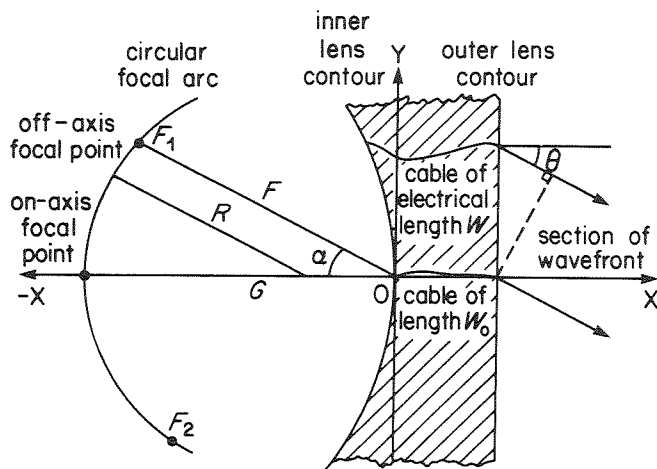
50 Ω lines

Fig. 8 - Rotman lens parameters.

focal point out to the corresponding radiated wavefront for each element of the array, see Fig. 8. The beam ports would be placed on the circular focal arc, whilst the array ports are on the lens contour.

7.1 Design of a Rotman lens

The positions of the beam ports are defined by the required angular beam directions from the array. These are determined by the orthogonal beam set which will cover the required angular range once the fixed phase slew is applied. The Rotman lens design provides three perfect focal points and these can be chosen to coincide with three of the beam ports, resulting in no theoretical phase errors at these ports[9]. One focal point will be at the mid-point of the beam port contour and the angle to the offset focal points, α, is chosen so that the phase aberrations at intermediate beam ports are minimised. However, phase aberrations from the design of the lens are usually less than $1°$, unless a particularly wide slew angle is required, and these are insignificant compared to other sources of error.

The on-axis focal length of the array, G, is chosen so that the lens does not become wider than it is long and also to ensure that the array port contour has a reasonable curvature. As G is reduced, the array port contour has to become more curved to produce the same taper across the array. This can lead to very low amplitude signals being received by the end array ports because of their angular position with respect to the beam ports. Another condition which has to be satisfied is that the array ports should be in the far-field of the beam ports. If this is not the case, there will be a quadratic phase error across the array ports. This condition gives a minimum value for G.

The off-axis focal length F determines the relative curvature of the beam and array port

contours. As F is reduced compared to G, the beam port contour becomes more curved and the array port contour opens up. This is because the relationship between the path lengths from each beam port to each array port is fixed, and is given by the beam slew required. The relationship $g = G/F$ is used to describe this design variable, and therefore a 'Rotman $g = 1$' lens has $G = F$ and the beam port contour is an arc of a circle centred on the mid-point of the array port contour. This design has the advantage that the beam ports will be normal to the contour and will automatically point at the mid-point of the array port contour. This is important to ensure a fairly symmetrical amplitude distribution across the array ports.

The design of a Rotman $g = 1$ lens is such that the array port contour is a section of an ellipse and the array ports, if normal to the contour, will not point at the mid-point of the beam port contour. This results in the end array ports pointing at one end of the beam port contour giving in an uneven amplitude distribution within the lens. This has been overcome by angling the array ports to point at the mid-point of the beam port contour. Experiments have shown that this is successful for the relatively narrow aperture array ports which have wide beamwidths inside the lens, but the wide aperture, narrow beamwidth beam ports could not be pointed so easily. This lends weight to the argument that the $g = 1$ lens design should be used so that only the array ports have to be angled.

The apertures of the array ports relate to the element spacing of the array and the required phase taper and are therefore predetermined. The apertures of the beam ports, however, depend on the angular spacing of the required beams and the focal length of the lens. The result is a compromise between narrow apertures which would illuminate the array port contour fairly evenly, but would direct a significant amount of power beyond the edges of the contour; and wide beam ports which would not illuminate the end ports very strongly. Beam port apertures of around two wavelengths give a satisfactory cosine illumination of the array port contour with the end ports about 20 dB down on the centre ports.

The proposed flat-plate antenna has 50 by 32 elements arranged as 50 sub-arrays of 32 elements. It is steered in the plane of the sub-arrays, that is, the lens has to provide 50 phased outputs. This would require a very large lens of about 1.25 m by 0.8 m which is unfortunately too wide for the material currently available. Thus a half-size experimental lens was developed which would steer just 24 sub-arrays, but over an angular sector similar to that required for the large array.
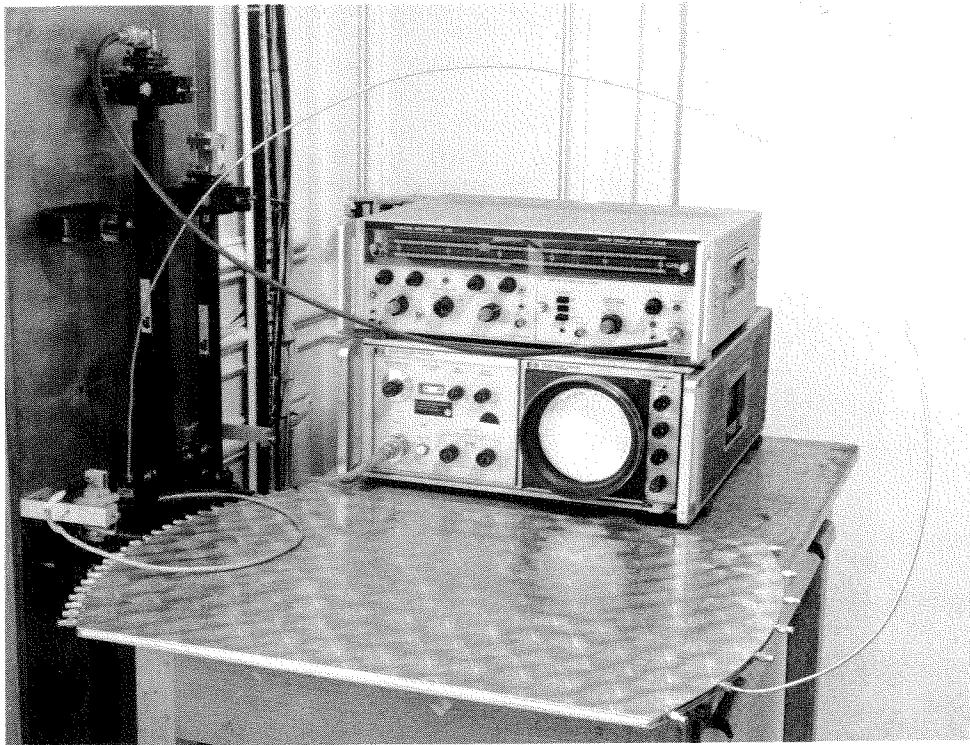
Fig. 9
Measuring the transmission coefficients of the lens.

The equations used to design the lens are given in Ref. 6.

A Rotman $g = 1$ lens design was used to produce the required phase tapers for each beam position. The lens contour coordinates were obtained from the design parameters by calculating the path lengths required from each input port to each output port for every beam slew required. The theoretical transmission coefficients for each port can also be evaluated from the geometrical configuration allowing the theoretical performance of the lens to be compared to the measured values.

7.2 Experimental results

The transmission coefficients of the lens are measured with a network analyser to ensure that it provides the required phase taper and amplitude distribution. The measurement system is shown connected to the lens in Fig. 9. A reference signal is input to one beam port at a time and the phase and amplitude of the signal at each array port is noted.

The measured phase tapers produced by the lens are compared with the predicted phases in Fig. 10. These results do not include the fixed beam slew and so the beams will be centred around broadside. It can be seen that the phase error increases towards the ends of the array port contour. At these array ports the amplitude of the wanted signal is small and internal reflections and spurious transmission modes within the lens can upset the output phase. In particular, reflections which occur at the connectors on

the array port contour tend to focus back through the lens, reflect from the beam port connectors and arrive back at the array ports with some variable phase relationship with the wanted signals. These triple transitions* can cause both phase and amplitude ripples in the lens outputs.

The total loss introduced by the lens is a combination of the lens design loss and the constructional losses. The design loss is the amount of energy which is directed at the sidewalls inside the lens. It varies depending on the beam port being used but is around 0.5 dB. Constructional losses include the copper loss, the dielectric loss and mismatches at the connectors. There will also be some power coupled into unwanted parallel plate transmission modes and these factors will all tend to reduce the amplitudes of the signals at the array ports. The insertion loss of the lens can be calculated from the amplitude distribution and ranges from 1.5 to 2.4 dB depending on variables such as the theoretical design loss for each beam port and the reflection coefficients at each connector.

The amplitude distribution for Beam Port 0† is given in Fig. 11 and the results for the other beam ports are very similar. In general, the measured amplitudes were lower than the predicted values.

---

* In the literature on microwave lenses, these refelections are referred to as 'triple transitions'. However engineers with experience of surface accoustic wave (SAW) devices will be more familiar with the alternative phrase of 'triple transit echoes'.

† The Beam Port and Array Port numbering starts at 0 because there is zero displacement between the first array element and the end of the array and therefore the numbers conveniently relate to element spacings.
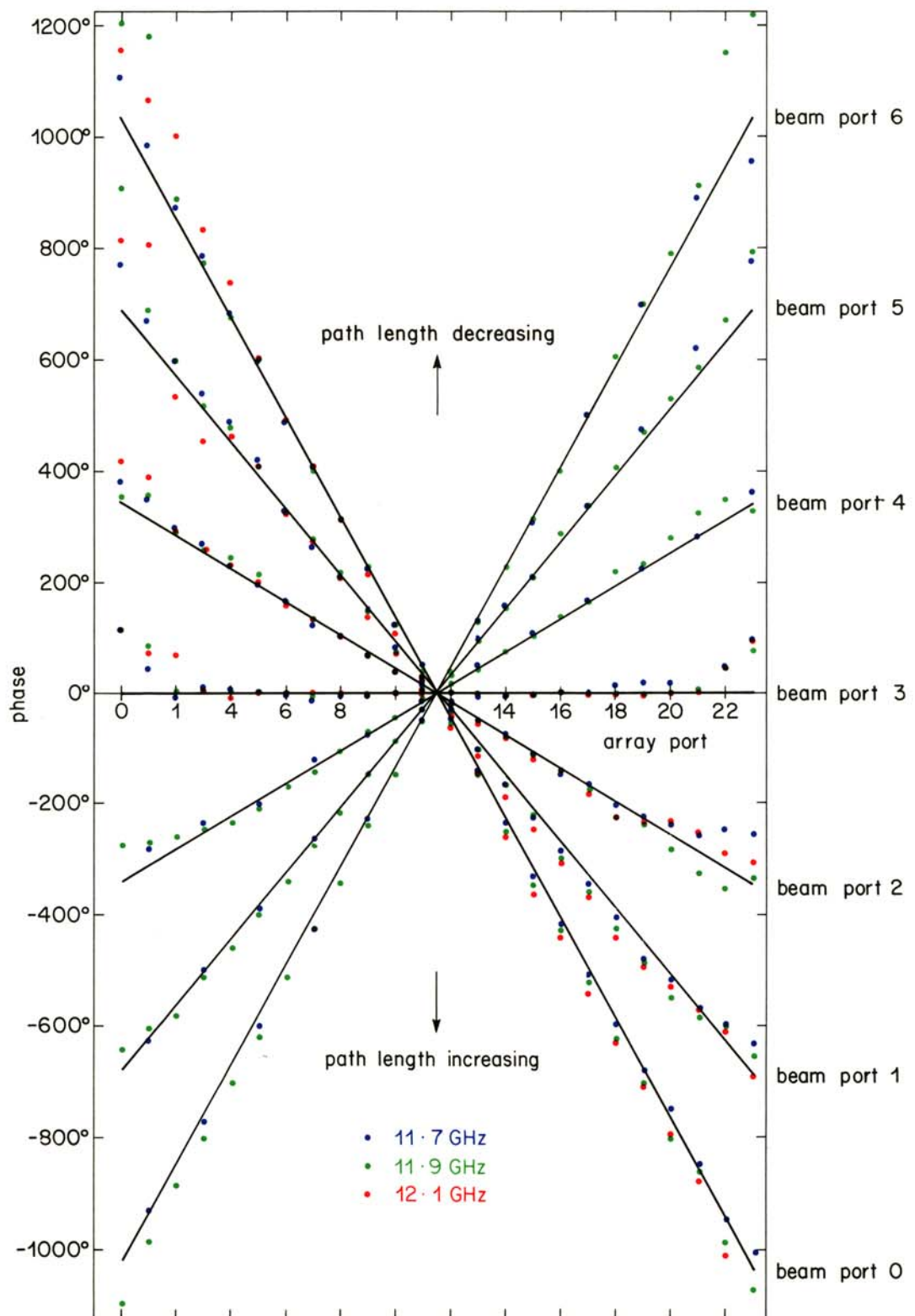
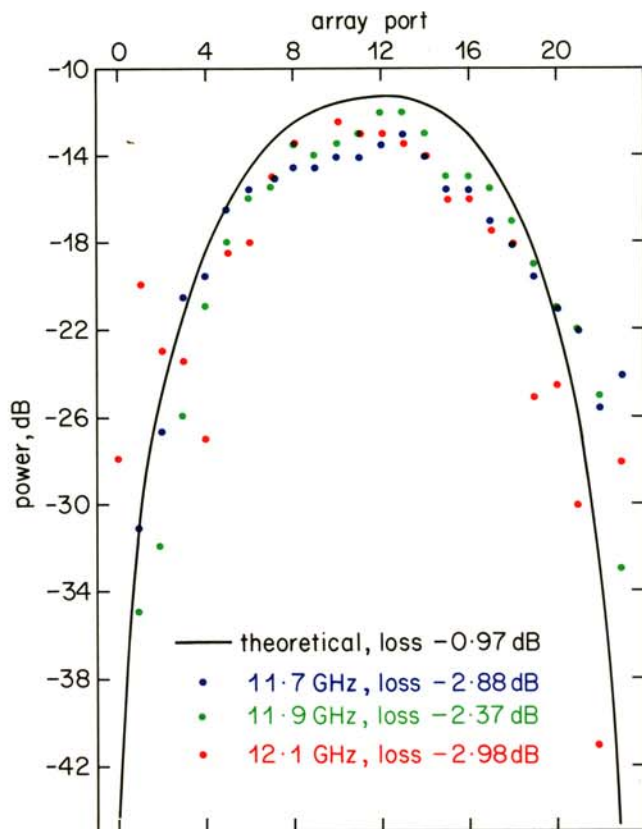*Fig. 10 - Measured phase taper produced by the lens compared with the predicted values.*

Fig. 11 - Amplitude distribution for Beam Port 0 compared with the predicted distribution.

However, at the end array ports the output becomes larger than the wanted amplitude, lending weight to the argument that the internal reflections and spurious propagation modes have a larger amplitude than the wanted outputs at these ports.

To establish the effect of the phase and amplitude errors on the beam shapes produced by the lens, the measured phase and amplitude results can be applied to a theoretical array of 24 cardioid elements in a program to plot the radiation pattern. Fig. 12 shows the beam shape produced by Beam Port 0 compared with the beam shape predicted by the calculated phase and amplitude performance of the lens. It can be seen that the phase and amplitude errors raise the sidelobes and fill the nulls of the radiation pattern. Further investigation indicated that it was not the large phase errors on the end array ports causing the pattern degradations, because their amplitudes were so small. The degradation appears to be caused by a combination of the smaller phase errors and the amplitude ripple on the centre array ports.

The angular positions of the beams are generally within 0.5° of their predicted positions as shown in Fig. 13. This plots the beam shapes resulting from a theoretical array of 24 cardioid elements

excited by the measured phase and amplitude distributions for all seven beam ports.

The coaxial lines connecting the lens to the array vary in length to produce the fixed phase slew required to slew all the lens beams to one side of broadside. The beams are shifted in sin ϕ space and remain orthogonal although their relative spacings change. The beams become wider as the scan angle becomes further from broadside, so their relative spacing increases slightly. These cables and their connectors have a loss of around 0.5 dB resulting in a total insertion loss for the beamforming network of up to 3 dB.

8. CONCLUSIONS

It has been demonstrated that it is possible to provide a feed system that will allow an experimental flat-plate antenna to be steered electrically to point at a DBS satellite. It has also proved to be possible to construct the feed using low-cost materials which lend themselves to the use of economical mass-production methods in manufacture.

Two types of feed structure have been considered for this application. The series feed configuration proved to be very complex to achieve a match for such a large sub-array. Hence, a corporate feed network has been designed and constructed to collect the energy from all the array elements in one plane and to connect to the beamforming network which will steer the array in the other plane. The feed structure introduced a loss of around 2 dB in the overall gain of the antenna.

A number of steering mechanisms and beam-forming devices have been considered for use with the flat-plate antenna. Most techniques were rejected because they require a large number of expensive microwave components. Other devices increase rapidly in complexity as the array size increases. A microwave lens is suitable for use with the flat-plate antenna because it is able to form beams from a large array fairly easily and can be made entirely using low-cost materials. A Rotman lens has been designed and constructed to produce seven beams from an experimental, half size antenna over the angular sector specified for DBS reception. The angular positions of the beams are within 0.5° of their predicted positions and the sidelobes generated by the lens are generally below −20 dB down. The lens contributes up to 3 dB to the overall losses of the feed to the antenna.

The losses introduced by the feed structure and the lens could be reduced by changing the construction techniques in a production prototype. A significant
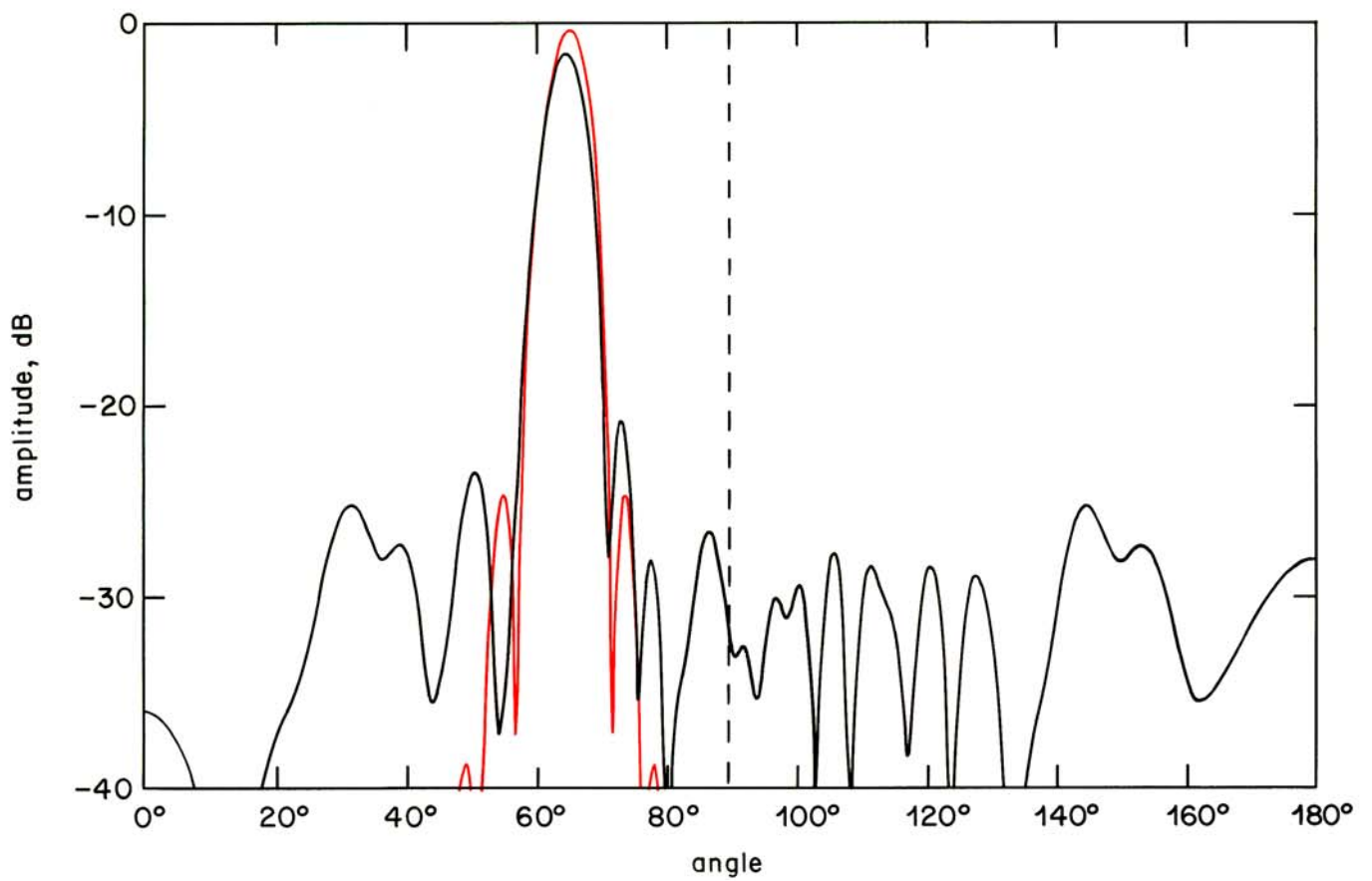
Fig. 12 - Beam shape produced by Beam Port 0 (black) compared with the predicted lens performance (red).
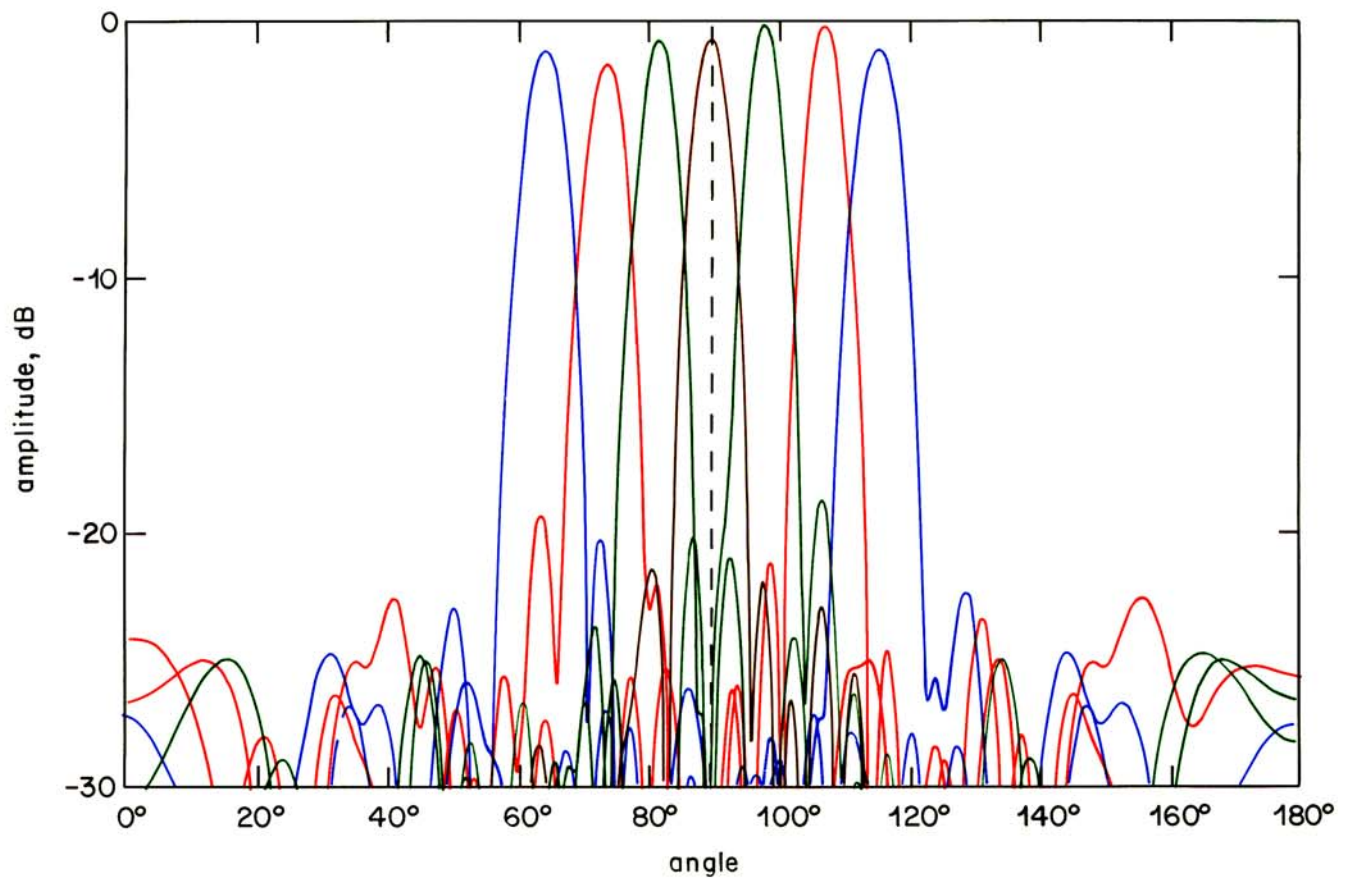

Fig. 13 - Relative angular positions of the seven beams formed by the Rotman lens.

amount of the loss is caused by interconnecting cables, SMA connectors and triplate launchers. It is envisaged that these could be eliminated in a final production antenna by using transmission lines etched in the same way as the feed to interconnect between the sub-arrays and feed structures. It is possible that the overall antenna gain would be significantly improved with such a feed system.

It is considered that a Rotman lens could prove attractive for steering the beam of a flat-plate antenna for DBS reception. A corporate feed has been implemented although a series feed had better attenuation properties and should not be neglected. Further development work would concentrate on minimising the losses throughout the system.

9. ACKNOWLEDGEMENT

10. REFERENCES

1. MADDOCKS, M.C.D. 1988. A flat-plate antenna for DBS reception. BBC Research Department Report No. BBC RD 1988/6.

2. MADDOCKS, M.C.D. 1988. Array elements for a DBS flat-plate antenna. BBC Research Department Report No. BBC RD 1988/8.

3. MADDOCKS, M.C.D. and BOARDMAN, D.H. 1988. Polarisation converters for DBS flat-plate antennas. BBC Research Department Report No. BBC RD 1988/7.

4. RAMOS, E. 1984. Suspended substrate line antenna fits 12 GHz satellite applications. *Microwave Systems News*, March 1984.

5. JAMES, HALL and WOOD. 1981. Microstrip antenna theory and design. Chapter 5, Linear array techniques. Peter Peregrinus Ltd. ISBN 0906048 575.

6. SMITH, M.S. 1982. Design considerations for Ruze and Rotman lenses. *The Radio and Electronic Engineer*, Vol. 52, No. 4, April 1982.

7. JOHNSON, R.C. and JASIK, H. 1988. Antenna engineering handbook, Second Edition. McGraw-Hill, 1988. Section 20-5 Feed network design for phased arrays.

8. MATTHAEI, YOUNG and JONES. 1964. Microwave filters, impedance matching networks and coupling structures. McGraw-Hill.

9. ROTMAN, W. and TURNER, R.F. 1963. Wide-angle microwave lens for line source applications. *IEEE Transactions on Antennas and Propagation*, No. 11, 1963.